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(54) **VEIN MATCHING FOR DIFFICULT BIOMETRIC AUTHENTICATION CASES**

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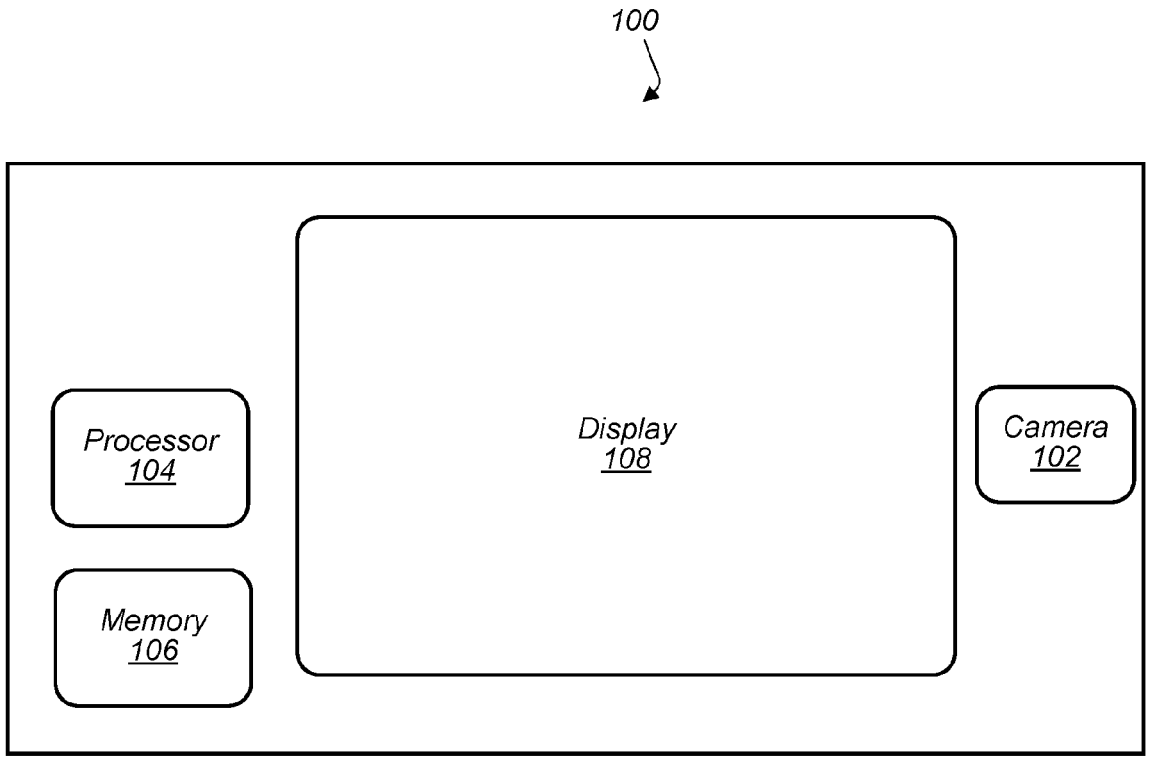
(57) **ABSTRACT**

Subepidermal imaging of a face may be used to assess subepidermal features such as blood vessels (e.g., veins) when the device is attempting to authenticate a user in a facial recognition authentication process. Assessment of the subepidermal features may be used to distinguish between users that have closely related facial features (e.g., siblings or twins) in situations where the facial recognition authentication process has less certainty in a decision about recognition of the user's face as an authorized user.



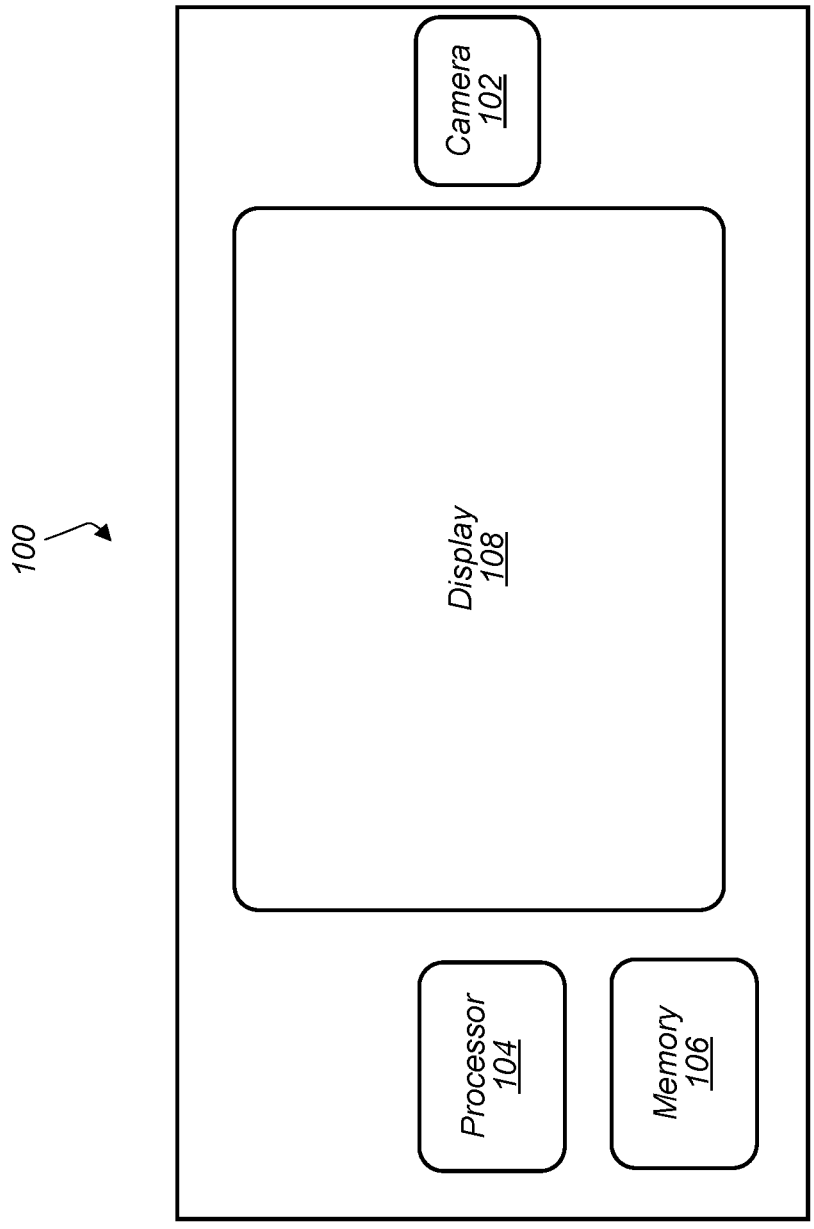


FIG. 1

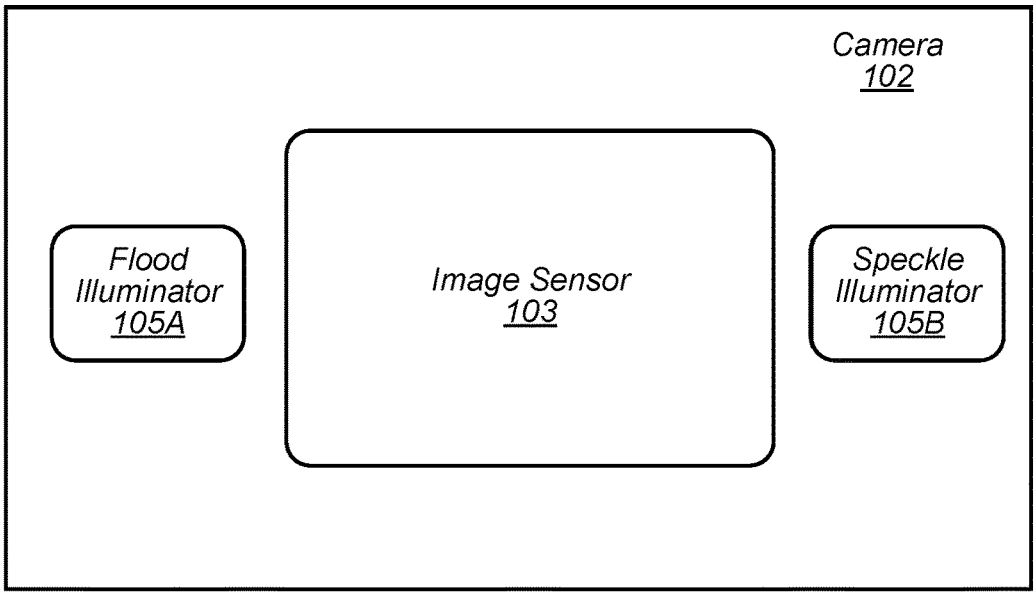

Camera
102
Flood
Illuminator
105A
Image Sensor
103
Speckle
Illuminator
105B

FIG. 2

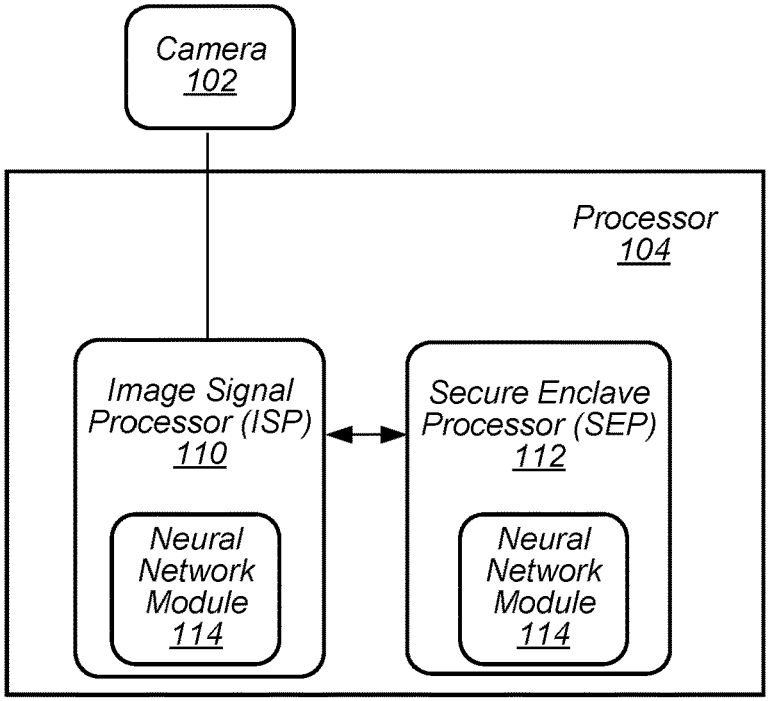

Camera
102
Processor
104
Image Signal
Processor (ISP)
110
Neural
Network
Module
114
Secure Enclave
Processor (SEP)
112
Neural
Network
Module
114

FIG. 3

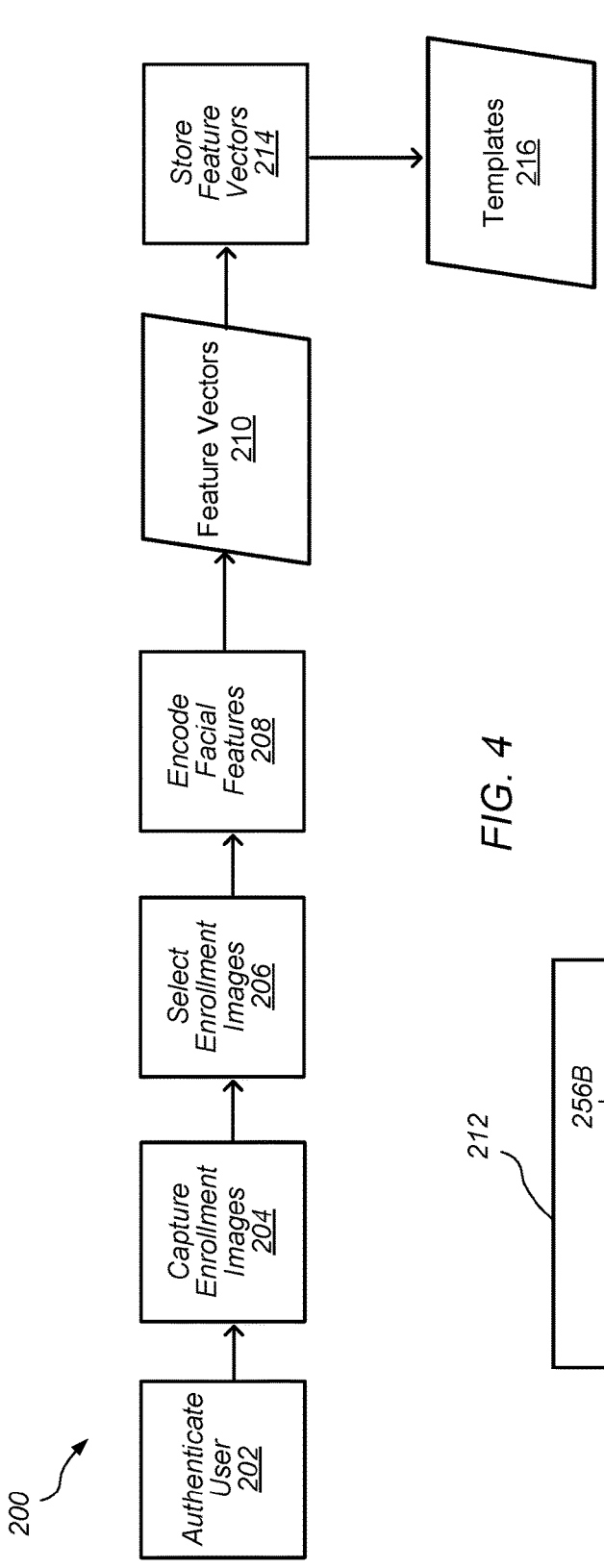


FIG. 4

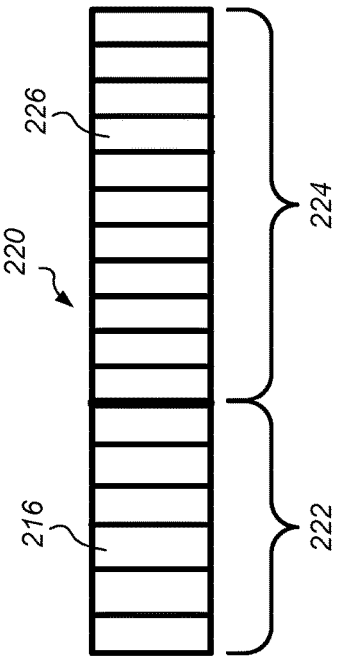


FIG. 6

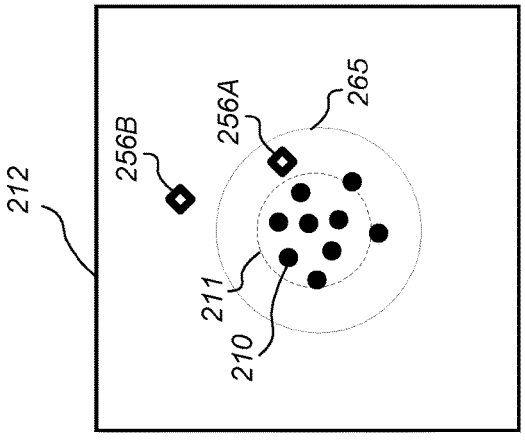


FIG. 5

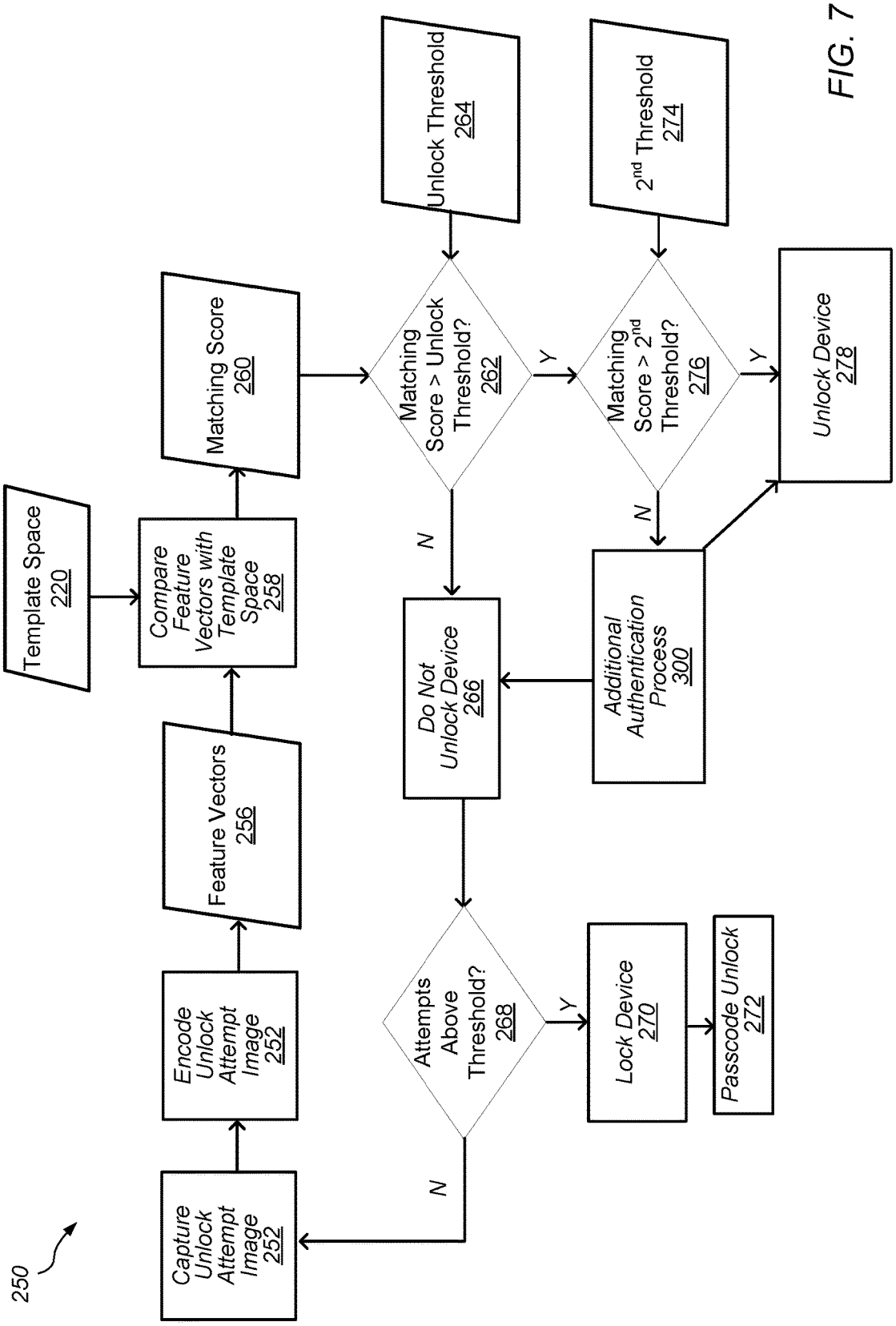

250
Capture Unlock Attempt Image 252
Encode Unlock Attempt Image 252
Feature Vectors 256
Compare Feature Vectors with Template Space 258
Template Space 220
Matching Score 260
Matching Score > Unlock Threshold? 262
Unlock Threshold 264
Y
N
Matching Score > 2nd Threshold? 276
2nd Threshold 274
Y
N
Unlock Device 278
Additional Authentication Process 300
Do Not Unlock Device 266
Attempts Above Threshold? 268
Y
N
Lock Device 270
Passcode Unlock 272

FIG. 7

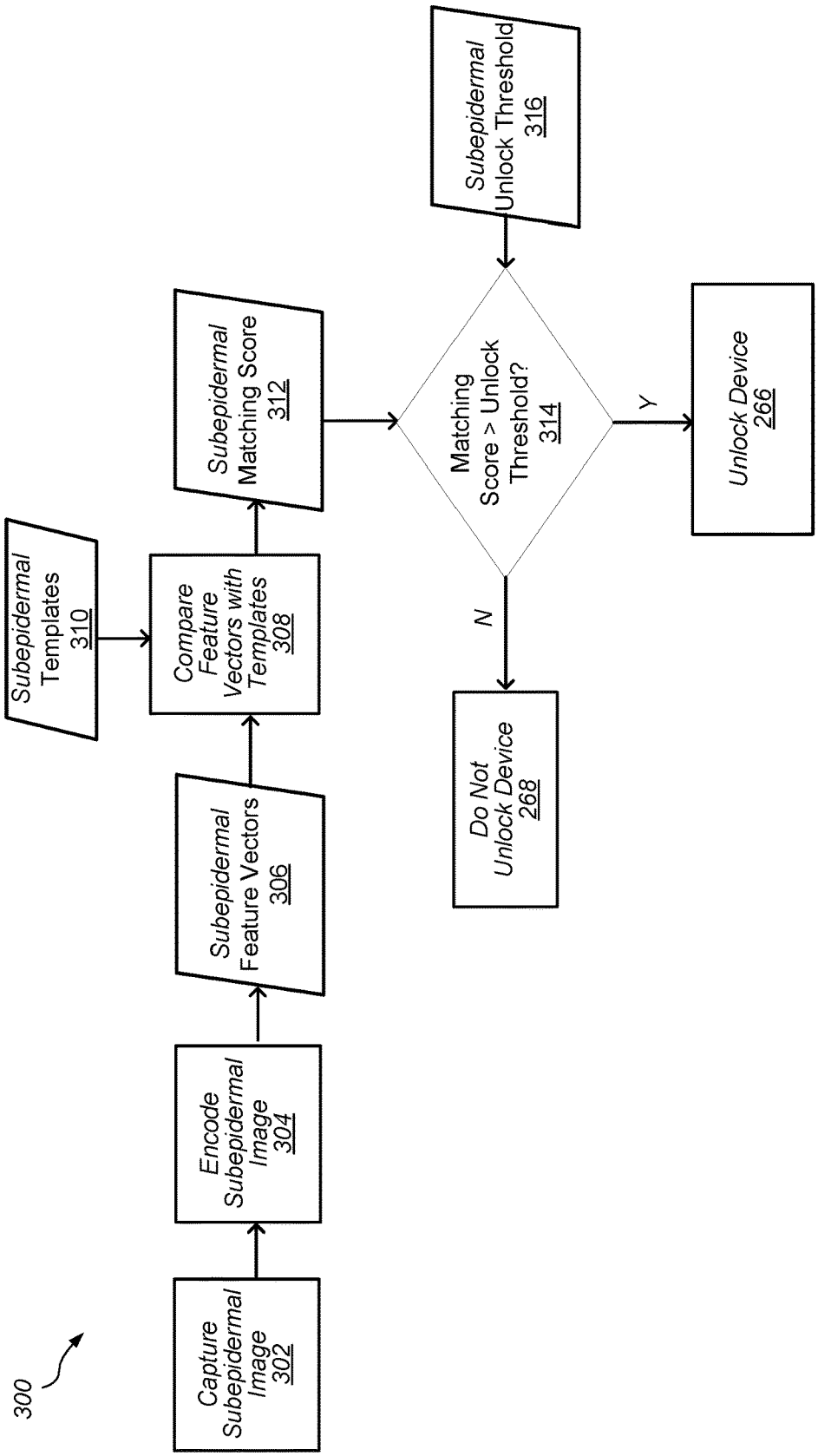

300
Capture Subepidermal Image 302
Encode Subepidermal Image 304
Subepidermal Feature Vectors 306
Compare Feature Vectors with Templates 308
Subepidermal Templates 310
Subepidermal Matching Score 312
Matching Score > Unlock Threshold? 314
Subepidermal Unlock Threshold 316
Y
N
Unlock Device 266
Do Not Unlock Device 268

FIG. 8

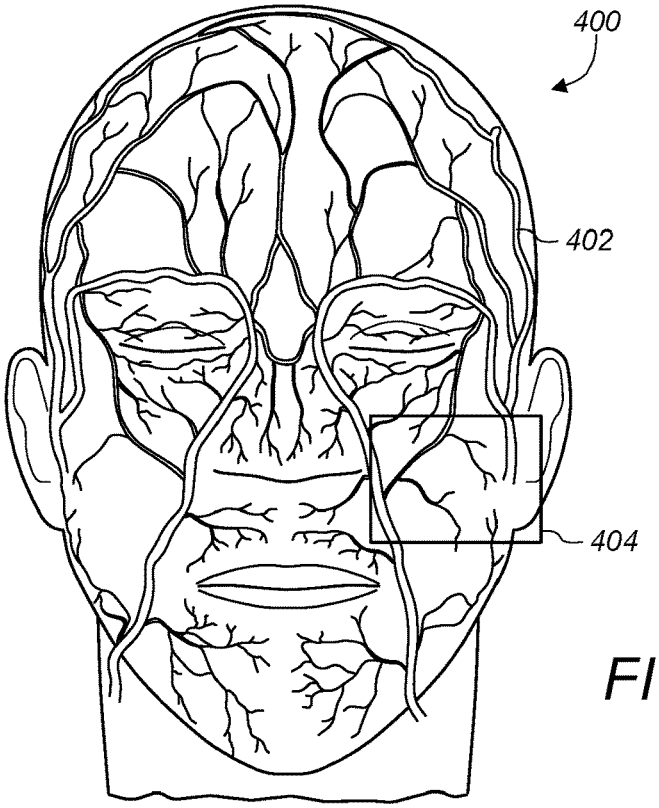


FIG. 9

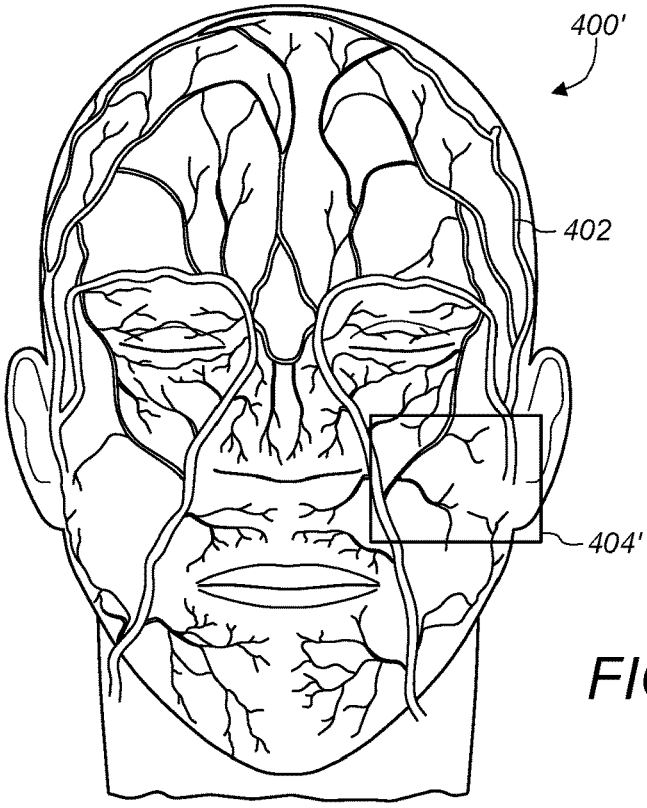


FIG. 10

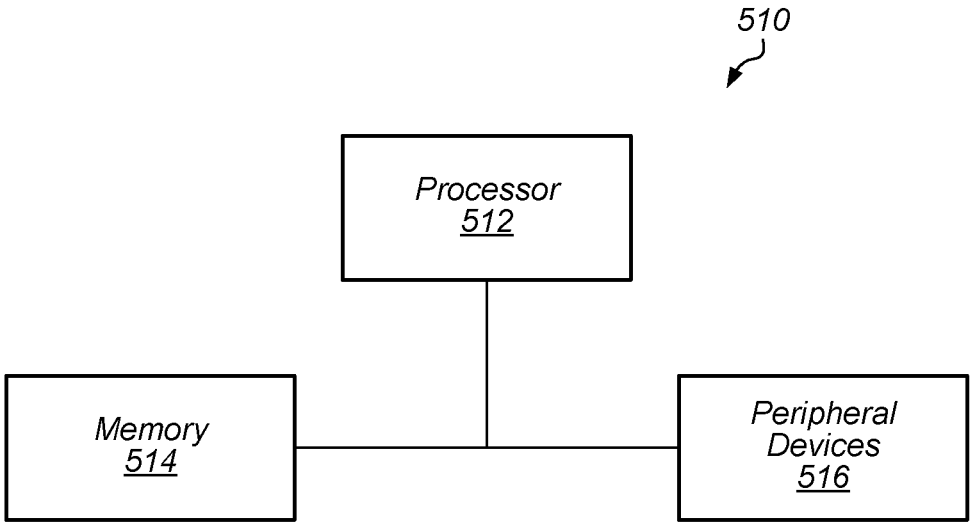

510
Processor
512
Memory
514
Peripheral
Devices
516

FIG. 11

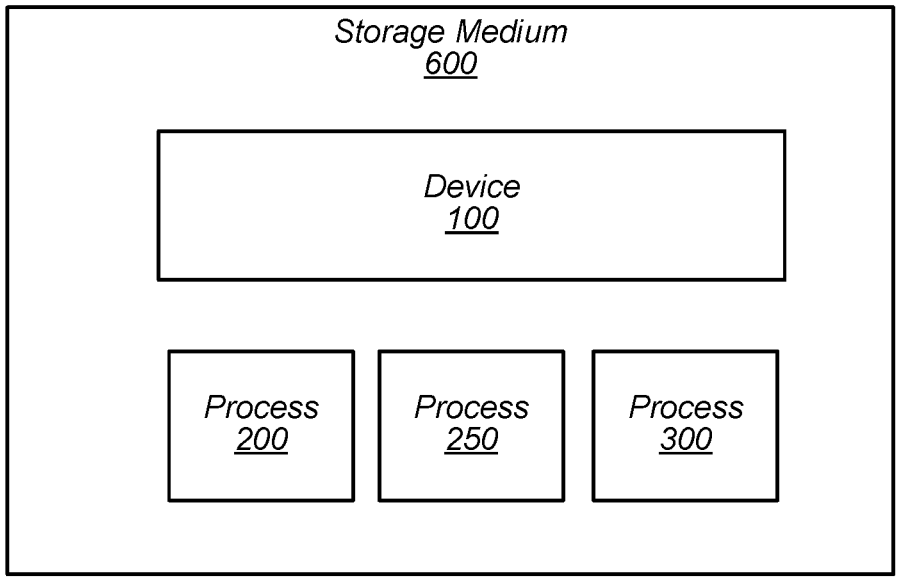

Storage Medium
600
Device
100
Process
200
Process
250
Process
300

FIG. 12

VEIN MATCHING FOR DIFFICULT BIOMETRIC AUTHENTICATION CASES

PRIORITY CLAIM

[0001] This patent claims priority to U.S. Provisional Patent Application No. 62/556,405 to Kalscheur et al., entitled "VEIN MATCHING FOR DIFFICULT BIOMETRIC AUTHENTICATION CASES", filed Sep. 9, 2017; and to U.S. Provisional Patent Application No. 62/556,812 to Kalscheur et al., entitled "VEIN MATCHING FOR DIFFICULT BIOMETRIC AUTHENTICATION CASES", filed Sep. 11, 2017; each of which are incorporated by reference in their entirety.

BACKGROUND

1. Technical Field

[0002] Embodiments described herein relate to methods and systems for face detection in images capture by a camera on a device.

2. Description of Related Art

[0003] Biometric authentication processes are being used more frequently to allow users to more readily access their devices without the need for passcode or password authentication. One example of a biometric authentication process is fingerprint authentication using a fingerprint sensor. Facial recognition is another biometric process that may be used for authentication of an authorized user of a device. Facial recognition processes are generally used to identify individuals in an image and/or compare individuals in images to a database of individuals to match the faces of individuals.

[0004] For authentication using facial recognition, there are potential cases where a user attempting to be authenticated (authorized) by a device cannot be distinguished from another user with closely related facial features. For example, it may be difficult for a facial recognition authentication process to distinguish between siblings, twins, and other closely related faces. When the authentication process cannot distinguish between closely related faces, additional authentication processes may be used to reduce or prevent increases in a false acceptance rate.

SUMMARY

[0005] Subepidermal imaging of a face of a user attempting to unlock a device may be used to enhance a facial recognition authentication process (e.g., enhance the security of the facial recognition authentication process). Subepidermal images of the user may be used to assess subepidermal features such as blood vessels (e.g., veins) when the device is attempting to authenticate the user. The subepidermal features may be compared to templates of subepidermal features for an authorized (e.g., enrolled) user of the device. Assessment of subepidermal features during the facial recognition authentication process may be useful in distinguishing between users that have closely related facial features (e.g., siblings or twins). In addition, assessment of subepidermal features may be used to prevent unlocking of the device by an unauthorized user wearing a mask or using another face replication method.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] Features and advantages of the methods and apparatus of the embodiments described in this disclosure will be more fully appreciated by reference to the following detailed description of presently preferred but nonetheless illustrative embodiments in accordance with the embodiments described in this disclosure when taken in conjunction with the accompanying drawings in which:

[0007] FIG. **1** depicts a representation of an embodiment of a device including a camera.

[0008] FIG. **2** depicts a representation of an embodiment of a camera.

[0009] FIG. **3** depicts a representation of an embodiment of a processor on a device.

[0010] FIG. **4** depicts a flowchart of an embodiment of an image enrollment process for an authorized user of a device.

[0011] FIG. **5** depicts a representation of an embodiment of a feature space with feature vectors after an enrollment process.

[0012] FIG. **6** depicts a representation of an embodiment of a template space of a memory.

[0013] FIG. **7** depicts a flowchart of an embodiment of facial recognition authentication process.

[0014] FIG. **8** depicts a flowchart of an embodiment of additional authentication process.

[0015] FIG. **9** depicts a representation of an embodiment of an image of subepidermal features in a user's face.

[0016] FIG. **10** depicts a representation of another embodiment of an image of sub epidermal features in a user's face.

[0017] FIG. **11** depicts a block diagram of one embodiment of an exemplary computer system.

[0018] FIG. **12** depicts a block diagram of one embodiment of a computer accessible storage medium.

[0019] While embodiments described in this disclosure may be susceptible to various modifications and alternative forms, specific embodiments thereof are shown by way of example in the drawings and will herein be described in detail. It should be understood, however, that the drawings and detailed description thereto are not intended to limit the embodiments to the particular form disclosed, but on the contrary, the intention is to cover all modifications, equivalents and alternatives falling within the spirit and scope of the appended claims. The headings used herein are for organizational purposes only and are not meant to be used to limit the scope of the description. As used throughout this application, the word "may" is used in a permissive sense (i.e., meaning having the potential to), rather than the mandatory sense (i.e., meaning must). Similarly, the words "include", "including", and "includes" mean including, but not limited to.

[0020] Various units, circuits, or other components may be described as "configured to" perform a task or tasks. In such contexts, "configured to" is a broad recitation of structure generally meaning "having circuitry that" performs the task or tasks during operation. As such, the unit/circuit/component can be configured to perform the task even when the unit/circuit/component is not currently on. In general, the circuitry that forms the structure corresponding to "configured to" may include hardware circuits and/or memory storing program instructions executable to implement the operation. The memory can include volatile memory such as static or dynamic random access memory and/or nonvolatile memory such as optical or magnetic disk storage, flash

memory, programmable read-only memories, etc. The hardware circuits may include any combination of combinatorial logic circuitry, clocked storage devices such as flops, registers, latches, etc., finite state machines, memory such as static random access memory or embedded dynamic random access memory, custom designed circuitry, programmable logic arrays, etc. Similarly, various units/circuits/components may be described as performing a task or tasks, for convenience in the description. Such descriptions should be interpreted as including the phrase "configured to." Reciting a unit/circuit/component that is configured to perform one or more tasks is expressly intended not to invoke 35 U.S.C. § 112(f) interpretation for that unit/circuit/component.

[0021] In an embodiment, hardware circuits in accordance with this disclosure may be implemented by coding the description of the circuit in a hardware description language (HDL) such as Verilog or VHDL. The HDL description may be synthesized against a library of cells designed for a given integrated circuit fabrication technology, and may be modified for timing, power, and other reasons to result in a final design database that may be transmitted to a foundry to generate masks and ultimately produce the integrated circuit. Some hardware circuits or portions thereof may also be custom-designed in a schematic editor and captured into the integrated circuit design along with synthesized circuitry. The integrated circuits may include transistors and may further include other circuit elements (e.g. passive elements such as capacitors, resistors, inductors, etc.) and interconnect between the transistors and circuit elements. Some embodiments may implement multiple integrated circuits coupled together to implement the hardware circuits, and/or discrete elements may be used in some embodiments.

[0022] The scope of the present disclosure includes any feature or combination of features disclosed herein (either explicitly or implicitly), or any generalization thereof, whether or not it mitigates any or all of the problems addressed herein. Accordingly, new claims may be formulated during prosecution of this application (or an application claiming priority thereto) to any such combination of features. In particular, with reference to the appended claims, features from dependent claims may be combined with those of the independent claims and features from respective independent claims may be combined in any appropriate manner and not merely in the specific combinations enumerated in the appended claims.

DETAILED DESCRIPTION OF EMBODIMENTS

[0023] This specification includes references to "one embodiment" or "an embodiment." The appearances of the phrases "in one embodiment" or "in an embodiment" do not necessarily refer to the same embodiment, although embodiments that include any combination of the features are generally contemplated, unless expressly disclaimed herein. Particular features, structures, or characteristics may be combined in any suitable manner consistent with this disclosure.

[0024] The present disclosure further contemplates that the entities responsible for the collection, analysis, disclosure, transfer, storage, or other use of such personal information data will comply with well-established privacy policies and/or privacy practices. In particular, such entities should implement and consistently use privacy policies and practices that are generally recognized as meeting or exceeding industry or governmental requirements for maintaining personal information data private and secure. For example, in the case of unlocking and/or authorizing devices using facial recognition, personal information from users should be collected for legitimate and reasonable uses of the entity and not shared or sold outside of those legitimate uses. Further, such collection should occur only after receiving the informed consent of the users. Additionally, such entities would take any needed steps for safeguarding and securing access to such personal information data and ensuring that others with access to the personal information data adhere to their privacy policies and procedures. Further, such entities can subject themselves to evaluation by third parties to certify their adherence to widely accepted privacy policies and practices.

[0025] Despite the foregoing, the present disclosure also contemplates embodiments in which users selectively block the use of, or access to, personal information data. That is, the present disclosure contemplates that hardware and/or software elements can be provided to prevent or block access to such personal information data. For example, the present technology can be configured to allow users to select to "opt in" or "opt out" of participation in the collection of personal information data during registration for services.

[0026] FIG. **1** depicts a representation of an embodiment of a device including a camera. In certain embodiments, device **100** includes camera **102**, processor **104**, memory **106**, and display **108**. Device **100** may be a small computing device, which may be, in some cases, small enough to be handheld (and hence also commonly known as a handheld computer or simply a handheld). In certain embodiments, device **100** is any of various types of computer systems devices which are mobile or portable and which perform wireless communications using WLAN communication (e.g., a "mobile device"). Examples of mobile devices include mobile telephones or smart phones, and tablet computers. Various other types of devices may fall into this category if they include wireless or RF communication capabilities (e.g., Wi-Fi, cellular, and/or Bluetooth), such as desktop computers, laptop computers, portable gaming devices, portable Internet devices, and other handheld devices, as well as wearable devices such as smart watches, smart glasses, headphones, pendants, earpieces, etc. In general, the term "mobile device" can be broadly defined to encompass any electronic, computing, and/or telecommunications device (or combination of devices) which is easily transported by a user and capable of wireless communication using, for example, WLAN, Wi-Fi, cellular, and/or Bluetooth. In certain embodiments, device **100** includes any device used by a user with processor **104**, memory **106**, and display **108**. Display **108** may be, for example, an LCD screen or touchscreen. In some embodiments, display **108** includes a user input interface for device **100** (e.g., the display allows interactive input for the user).

[0027] Camera **102** may be used to capture images of the external environment of device **100**. In certain embodiments, camera **102** is positioned to capture images in front of display **108**. Camera **102** may be positioned to capture images of the user (e.g., the user's face) while the user interacts with display **108**. FIG. **2** depicts a representation of an embodiment of camera **102**. In certain embodiments, camera **102** includes one or more lenses and one or more image sensors **103** for capturing digital images. Digital images captured by camera **102** may include, for example, still images, video images, and/or frame-by-frame images.

[0028] In certain embodiments, camera **102** includes image sensor **103**. Image sensor **103** may be, for example, an array of sensors. Sensors in the sensor array may include, but not be limited to, charge coupled device (CCD) and/or complementary metal oxide semiconductor (CMOS) sensor elements to capture infrared images (IR) or other non-visible electromagnetic radiation. In some embodiments, camera **102** includes more than one image sensor to capture multiple types of images. For example, camera **102** may include both IR sensors and RGB (red, green, and blue) sensors. In certain embodiments, camera **102** includes illuminators **105** for illuminating surfaces (or subjects) with the different types of light detected by image sensor **103**. For example, camera **102** may include an illuminator for visible light (e.g., a "flash illuminator) and/or illuminators for infrared light (e.g., a flood IR source and a speckle pattern projector). In some embodiments, the flood IR source and speckle pattern projector are other wavelengths of light (e.g., not infrared). In certain embodiments, illuminators **105** include an array of light sources such as, but not limited to, VCSELs (vertical-cavity surface-emitting lasers). In some embodiments, image sensors **103** and illuminators **105** are included in a single chip package. In some embodiments, image sensors **103** and illuminators **105** are located on separate chip packages.

[0029] In certain embodiments, image sensor **103** is an IR image sensor used to capture infrared images used for face detection and/or depth detection. For face detection, illuminator **105**A may provide flood IR illumination to flood the subject with IR illumination (e.g., an IR flashlight) and image sensor **103** may capture images of the flood IR illuminated subject. Flood IR illumination images may be, for example, two-dimensional images of the subject illuminated by IR light. For depth detection or generating a depth map image, illuminator **105**B may provide IR illumination with a speckle pattern. The speckle pattern may be a pattern of light spots (e.g., a pattern of dots) with a known, and controllable, configuration and pattern projected onto a subject. Illuminator **105**B may include a VCSEL array configured to form the speckle pattern or a light source and patterned transparency configured to form the speckle pattern. The configuration and pattern of the speckle pattern provided by illuminator **105**B may be selected, for example, based on a desired speckle pattern density (e.g., dot density) at the subject. Image sensor **103** may capture images of the subject illuminated by the speckle pattern. The captured image of the speckle pattern on the subject may be assessed (e.g., analyzed and/or processed) by an imaging and processing system (e.g., an image signal processor (ISP) as described herein) to produce or estimate a three-dimensional map of the subject (e.g., a depth map or depth map image of the subject). Examples of depth map imaging are described in U.S. Pat. No. 8,150,142 to Freedman et al., U.S. Pat. No. 8,749,796 to Pesach et al., and U.S. Pat. No. 8,384,997 to Shpunt et al., which are incorporated by reference as if fully set forth herein, and in U.S. Patent Application Publication No. 2016/0178915 to Mor et al., which is incorporated by reference as if fully set forth herein. In some embodiments, other light pattern geometries may be used instead of, or in addition to, speckle pattern illumination. For example, geometries with grid lines of illumination or light pattern geometries that produce structured illumination patterns on the subject may be used for illumination of the subject.

[0030] In some embodiments, illuminator **105**A and/or illuminator **105**B provide IR illumination with a wavelength in a near-IR wavelength range (e.g., the wavelength may be in a range between about **780** nm and about **1050** nm) while image sensor **103** (e.g., a silicon sensor) captures images at such wavelengths. Infrared illumination in the near-IR wavelength range may be undetectable to a user of device **100** (e.g., the user cannot see light provided by illuminator **105**A and illuminator **105**B). In some embodiments, other IR wavelengths, or a combination of near-IR wavelengths, may be used instead of, or in addition to, the wavelength illumination in the near-IR range. In some embodiments, subepidermal images are captured when illuminating the face of the user with near-IR wavelength illumination. In some embodiments, another long wavelength illumination (e.g., long-wavelength IR with a range of wavelengths between about 10 μm and about 14 μm) may be used instead of, or in addition to, the wavelength illumination in the near-IR range.

[0031] In certain embodiments, images captured by camera **102** include images with the user's face (e.g., the user's face is included in the images). An image with the user's face may include any digital image with the user's face shown within the frame of the image. Such an image may include just the user's face or may include the user's face in a smaller part or portion of the image. The user's face may be captured with sufficient resolution in the image to allow image processing of one or more features of the user's face in the image.

[0032] Images captured by camera **102** may be processed by processor **104**. FIG. **3** depicts a representation of an embodiment of processor **104** included in device **100**. Processor **104** may include circuitry configured to execute instructions defined in an instruction set architecture implemented by the processor. Processor **104** may execute the main control software of device **100**, such as an operating system. Generally, software executed by processor **104** during use may control the other components of device **100** to realize the desired functionality of the device. The processors may also execute other software. These applications may provide user functionality, and may rely on the operating system for lower-level device control, scheduling, memory management, etc.

[0033] In certain embodiments, processor **104** includes image signal processor (ISP) **110**. ISP **110** may include circuitry suitable for processing images (e.g., image signal processing circuitry) received from camera **102**. ISP **110** may include any hardware and/or software (e.g., program instructions) capable of processing or analyzing images captured by camera **102**.

[0034] In certain embodiments, processor **104** includes secure enclave processor (SEP) **112**. In some embodiments, SEP **112** is involved in a facial recognition authentication process involving images captured by camera **102** and processed by ISP **110**. SEP **112** may be a secure circuit configured to authenticate an active user (e.g., the user that is currently using device **100**) as authorized to use device **100**. A "secure circuit" may be a circuit that protects an isolated, internal resource from being directly accessed by an external circuit. The internal resource may be memory (e.g., memory **106**) that stores sensitive data such as personal information (e.g., biometric information, credit card information, etc.), encryptions keys, random number generator seeds, etc. The internal resource may also be circuitry

that performs services/operations associated with sensitive data. As described herein, SEP **112** may include any hardware and/or software (e.g., program instructions) capable of authenticating a user using the facial recognition authentication process. The facial recognition authentication process may authenticate a user by capturing images of the user with camera **102** and comparing the captured images to previously collected images of an authorized user for device **100**. In some embodiments, the functions of ISP **110** and SEP **112** may be performed by a single processor (e.g., either ISP **110** or SEP **112** may perform both functionalities and the other processor may be omitted).

[0035] In certain embodiments, processor **104** performs an enrollment process (e.g., an image enrollment process or a registration process) to capture and store images (e.g., the previously collected images) for an authorized user of device **100**. During the enrollment process, camera module **102** may capture (e.g., collect) images and/or image data from an authorized user in order to permit SEP **112** (or another security process) to subsequently authenticate the user using the facial recognition authentication process. In some embodiments, the images and/or image data (e.g., feature data from the images) from the enrollment process are stored in a template in device **100**. The template may be stored, for example, in a template space in memory **106** of device **100**. In some embodiments, the template space may be updated by the addition and/or subtraction of images from the template. A template update process may be performed by processor **104** to add and/or subtract template images from the template space. For example, the template space may be updated with additional images to adapt to changes in the authorized user's appearance and/or changes in hardware performance over time. Images may be subtracted from the template space to compensate for the addition of images when the template space for storing template images is full.

[0036] In some embodiments, camera module **102** captures multiple pairs of images for a facial recognition session. Each pair may include an image captured using a two-dimensional capture mode (e.g., a flood IR image) and an image captured using a three-dimensional capture mode (e.g., a depth map image). In certain embodiments, ISP **110** and/or SEP **112** process the flood IR images and depth map images independently of each other before a final authentication decision is made for the user. For example, ISP **110** may process the images independently to determine characteristics of each image separately. SEP **112** may then compare the separate image characteristics with stored template images for each type of image to generate an authentication score (e.g., a matching score or other ranking of matching between the user in the captured image and in the stored template images) for each separate image. The authentication scores for the separate images (e.g., the flood IR and depth map images) may be combined to make a decision on the identity of the user and, if authenticated, allow the user to use device **100** (e.g., unlock the device).

[0037] In some embodiments, ISP **110** and/or SEP **112** combine the images in each pair to provide a composite image that is used for facial recognition. In some embodiments, ISP **110** processes the composite image to determine characteristics of the image, which SEP **112** may compare with the stored template images to make a decision on the identity of the user and, if authenticated, allow the user to use device **100**.

[0038] In some embodiments, the combination of flood IR image data and depth map image data may allow for SEP **112** to compare faces in a three-dimensional space. In some embodiments, camera module **102** communicates image data to SEP **112** via a secure channel. The secure channel may be, for example, either a dedicated path for communicating data (i.e., a path shared by only the intended participants) or a dedicated path for communicating encrypted data using cryptographic keys known only to the intended participants. In some embodiments, camera module **102** and/or ISP **110** may perform various processing operations on image data before supplying the image data to SEP **112** in order to facilitate the comparison performed by the SEP.

[0039] In certain embodiments, processor **104** operates one or more machine learning models. Machine learning models may be operated using any combination of hardware and/or software (e.g., program instructions) located in processor **104** and/or on device **100**. In some embodiments, one or more neural network modules **114** are used to operate the machine learning models on device **100**. Neural network modules **114** may be located in ISP **110** and/or SEP **112**.

[0040] Neural network module **114** may include any combination of hardware and/or software (e.g., program instructions) located in processor **104** and/or on device **100**. In some embodiments, neural network module **114** is a multi-scale neural network or another neural network where the scale of kernels used in the network can vary. In some embodiments, neural network module **114** is a recurrent neural network (RNN) such as, but not limited to, a gated recurrent unit (GRU) recurrent neural network or a long short-term memory (LSTM) recurrent neural network.

[0041] Neural network module **114** may include neural network circuitry installed or configured with operating parameters that have been learned by the neural network module or a similar neural network module (e.g., a neural network module operating on a different processor or device). For example, a neural network module may be trained using training images (e.g., reference images) and/or other training data to generate operating parameters for the neural network circuitry. The operating parameters generated from the training may then be provided to neural network module **114** installed on device **100**. Providing the operating parameters generated from training to neural network module **114** on device **100** allows the neural network module to operate using training information programmed into the neural network module (e.g., the training-generated operating parameters may be used by the neural network module to operate on and assess images captured by the device).

[0042] FIG. **4** depicts a flowchart of an embodiment of image enrollment process **200** for an authorized user of device **100**. Process **200** may be used to create one or more templates of images (e.g., an enrollment profile) for an authorized user of device **100** that are stored in the device (e.g., in a memory coupled to SEP **112**) and then used in a facial recognition process to allow the user to use the device (e.g., unlock the device). The enrollment profile (e.g., template of images) created by image enrollment process **200** may be associated that particular image enrollment process (and the images used to enroll during the process). For example, an authorized user may create a first enrollment profile associated with the user that includes the user's face with glasses. The authorized user may also create a second enrollment profile associated with the user that includes the

user's face without glasses. Each of the first and second enrollment profiles may then be used in the facial recognition process to allow the user to use the device (e.g., unlock the device).

[0043] In certain embodiments, process **200** is used when device **100** is used a first time by the authorized user and/or when the user opts to enroll in a facial recognition process. For example, process **200** may be initiated when device **100** is first obtained by the authorized user (e.g., purchased by the authorized user) and turned on for the first time by the authorized user. In some embodiments, process **200** may be initiated by the authorized user when the user desires to enroll in a facial recognition process, update security settings for device **100**, and/or re-enroll.

[0044] In certain embodiments, process **200** begins with authenticating the user in **202**. In **202**, the user may be authenticated on device **100** using a non-facial authentication process. For example, the user may be authenticated as an authorized user by entering a passcode, entering a password, or using another user authentication protocol other than facial recognition. After the user is authenticated in **202**, one or more enrollment (e.g., reference or registration) images of the user are captured in **204**. The enrollment images may include images of the user illuminated by flood illuminator **105**A (e.g., flood IR images) and/or images of the user illuminated by speckle illuminator **105**B (e.g., depth map images). As described herein, flood IR images and depth map images may be used independently and/or in combination in facial recognition processes on device **100** (e.g. the images may independently be used to provide an authentication decision and the decisions may be combined to determine a final decision on user authentication).

[0045] The enrollment images may be captured using camera **102** as the user interacts with device **100**. For example, the enrollment images may be captured as the user follows prompts on display **108** of device **100**. The prompts may include instructions for the user to make different motions and/or poses while the enrollment images are being captured. During **204**, camera **102** may capture multiple images for each motion and/or pose performed by the user. Capturing images for different motions and/or different poses of the user where the images still have a relatively clear depiction of the user may be useful in providing a better variety of enrollment images that enable the user to be authenticated without having to be in a limited or restricted position relative to camera **102** on device **100**.

[0046] After the multiple enrollment images are captured in **204**, selection of enrollment images for further image processing may be made in **206**. Selection of enrollment images **206**, and further processing of the images, may be performed by ISP **110** and/or SEP **112**. Selection of enrollment images for further processing may include selecting images that are suitable for use as template images. For example, the selection of images that are suitable for use as template images in **206** may include assessing one or more selected criteria for the images and selecting images that meet the selected criteria. The selected images may be used as template images for the user. Selected criteria may include, but not be limited to, the face of the user being in the field of view of the camera, a pose of the user being proper (e.g., the user's face is not turned to far in any direction from the camera (i.e., the pitch, yaw, and/or roll of the face are not above certain levels) a distance to the face of the user being within a certain distance, the face of the user having occlusion below a minimum value (e.g., the user's face is not occluded (blocked) more than a minimum amount by another object), the user paying attention to the camera (e.g., eyes of the user looking at the camera), eyes of the user not being closed, and proper lighting (illumination) in the image. In some embodiments, if more than one face is detected in an enrollment image, the enrollment image is rejected and not used (e.g., not selected) for further processing. Selection of images suitable for further processing may be rule based on the images meeting a certain number of the selected criteria or all of the selected criteria. In some embodiments, occlusion maps and/or landmark feature maps are used in identifying features of the user (e.g., facial features such as eyes, nose, and mouth) in the images and assessing the selected criteria in the images. In some embodiments, if the selected criteria are preventing the user from being enrolled (e.g., no enrollment images are being selected), then one or more of the selected criteria may be disabled to allow the user to be enrolled on the device. For example, occlusion criteria and/or attention criteria may be turned off/disabled if the user is having difficulty being enrolled.

[0047] After images are selected in **206**, features of the user in the selected (template) images may be encoded in **208**. Encoding of the selected images may include encoding features (e.g., facial features) of the user to define the features in the images as one or more feature vectors in a feature space. Feature vectors **210** may be the output of the encoding in **208**. A feature space may be an n-dimensional feature space. A feature vector may be an n-dimensional vector of numerical values that define features from the image in the feature space (e.g., the feature vector may be a vector of numerical values that define facial features of the user in the image).

[0048] FIG. **5** depicts a representation of an embodiment of feature space **212** with feature vectors **210**. Each feature vector **210** (black dot) may define facial features for the user from either a single image, from a composite image (e.g., an image that is a composite of several images), or from multiple images. As feature vectors **210** are generated from a single user's facial features, the feature vectors may be similar to one another because the feature vectors are associated with the same person and may have some "clustering", as shown by circle **211** in FIG. **5**. Feature vectors **256**A and **256**B (open diamonds) are feature vectors obtained from facial recognition process **250**, described below.

[0049] As shown in FIG. **4**, process **200** may include, in **214**, storing feature vectors **210** in a memory of device **100** (e.g., a memory protected by SEP **112**). In certain embodiments, feature vectors **210** are stored as static templates **216** (e.g., enrollment templates or reference templates) in a template space of the memory. In some embodiments, static templates **216** (and other templates described herein) include separate templates for feature vectors from the enrollment flood IR images and for feature vectors from the enrollment depth map images. It is to be understood that the separate templates for flood IR images and depth map images may be used independently and/or in combination during additional processes described herein. For simplicity in this disclosure, static templates **216** are described generically and it should be understood that static templates **216** (and the use of the templates) may refer to either templates for flood IR images or templates for depth map images. In some embodiments,

a combination of the flood IR images and depth map images may be used. For example, pairs of flood IR images and depth map images may be stored in static templates **216** to be used in one or more facial recognition processes on device **100**.

[0050] FIG. **6** depicts a representation of an embodiment of template space **220** of the memory. In some embodiments, template space **220** includes static portion **222** and dynamic portion **224**. Static templates **216** may be, for example, static templates added to static portion **222** of template space **220** (e.g., the templates are permanently added to the memory and are not deleted or changed unless the device is reset and another enrollment process takes place). In some embodiments, static portion **222** includes a certain number of static templates **216**. For example, for the embodiment of template space **220** depicted in FIG. **6**, six templates may be allowed in static portion **222**. After the enrollment process and the static templates **216** are added to static portion **222**, additional dynamic templates **226** may be added to dynamic portion **224** of template space **220** (e.g., a portion from which templates may be added and deleted without a device reset being needed).

[0051] Static templates **216** may thus be enrollment templates (or reference templates) generated by enrollment process **200**. After enrollment process **200** is completed, a selected number of static templates **216** are stored in static portion **222** of template space **220**. The number of static templates **216** stored in static portion **222** after enrollment process **200** may vary depending on, for example, the number of different feature vectors obtained during the enrollment process, which may be based on the number of images selected to be suitable for use as template images, or a desired number of templates for the device. After enrollment process **200**, static templates **216** include feature vectors **210** (e.g., the enrollment or reference feature vectors) that can be used for facial recognition of the authorized user. Template space **220** may then be used in a facial recognition authentication process.

[0052] FIG. **7** depicts a flowchart of an embodiment of facial recognition authentication process **250**. Process **250** may be used to authenticate a user as an authorized user of device **100** using facial recognition of the user. Authentication of the authorized user may allow the user to access and use device **100** (e.g., unlock the device) and/or have access to a selected functionality of the device (e.g., unlocking a function of an application running on the device, payment systems (i.e., making a payment), access to personal data, expanded view of notifications, etc.). In certain embodiments, process **250** is used as a primary biometric authentication process for device **100** (after enrollment of the authorized user). In some embodiments, process **250** is used as an authentication process in addition to another authentication process (e.g., fingerprint authentication, another biometric authentication, passcode entry, password entry, and/or pattern entry). In some embodiments, another authentication process (e.g., passcode entry, pattern entry, other biometric authentication) may be used to access device **100** if the user fails to be authenticated using process **250**.

[0053] In **252**, camera **102** captures an image of the face of the user attempting to be authenticated for access to device **100** (e.g., the camera captures an "unlock attempt" image of the user). It is to be understood that the unlock attempt image may be a single image of the face of the user (e.g., a single flood IR image or single depth map image) or the unlock attempt image may be a series of several images of the face of the user taken over a short period of time (e.g., one second or less). In some embodiments, the series of several images of the face of the user includes pairs of flood IR images and depth map images (e.g., pairs of consecutive flood IR and depth map images). In some implementations, the unlock attempt image may be a composite of several images of the user illuminated by the flood illuminator and the speckle pattern illuminator.

[0054] Camera **102** may capture the unlock attempt image in response to a prompt by the user. For example, the unlock attempt image may be captured when the user attempts to access to device **100** by pressing a button (e.g., a home button or virtual button) on device **100**, by moving the device into a selected position relative to the user's face (e.g., the user moves the device such that the camera is pointed directly at the user's face), and/or by making a specific gesture or movement with respect to the device. It is to be understood that, as described herein, unlock attempt images may include either flood IR images or depth map images, or a combination thereof. Further, the unlock attempt images may be processed in association with their corresponding template (e.g., flood IR images with a template for flood IR enrollment images) independently or in combination as needed.

[0055] In **254**, the unlock attempt image is encoded to define the facial features of the user as one or more feature vectors in the feature space. In some embodiments, one feature vector is defined for the unlock attempt image. In some embodiments, more than one feature vector is defined for the unlock attempt image. Unlock feature vector(s) **256** may be the output of the encoding of the unlock attempt image in **254**.

[0056] In certain embodiments, in **258**, unlock feature vector(s) **256** are compared to feature vectors in the templates of template space **220** to get matching score **260** for the unlock attempt image. Matching score **260** may be a score of the differences between feature vector(s) **256** and feature vectors in template space **220** (e.g., feature vectors in static templates **216** and/or other dynamic templates **226** added to the template space as described herein). The closer (e.g., the less distance or less differences) that feature vector(s) **256** and the feature vectors in template space **220** are, the higher matching score **260** may be. For example, as shown in FIG. **5**, feature vector **256**A (open diamond) is closer to feature vectors **210** than feature vector **256**B (open diamond)(e.g., feature vector **256**B is a further outlier than feature vector **256**A). Thus, feature vector **256**A would have a higher matching score than feature vector **256**A. As feature vector **256**B is further away from feature vectors **210** than feature vector **256**A, the lower matching score for feature vector **256**B means less confidence that the face in the unlock attempt image associated with feature vector **256**B is the face of the authorized user from enrollment process **200**.

[0057] In some embodiments, comparing feature vector(s) **256** and templates from template space **220** to get matching score **260** includes using one or more classifiers or a classification-enabled network to classify and evaluate the differences between feature vector(s) **256** and templates from template space **220**. Examples of different classifiers that may be used include, but are not limited to, linear, piecewise linear, nonlinear classifiers, support vector machines, and neural network classifiers. In some embodi-

ments, matching score **260** is assessed using distance scores between feature vector(s) **256** and templates from template space **220**.

[0058] In **262**, matching score **260** is compared to unlock threshold **264** for device **100**. Unlock threshold **264** may represent a minimum difference (e.g., distance in the feature space) in features (as defined by feature vectors) between the face of the authorized user and the face of the user in the unlock attempt image that device **100** requires in order to unlock the device (or unlock a feature on the device). For example, unlock threshold **264** may be a threshold value that determines whether the unlock feature vectors (e.g., feature vectors **256**) are similar enough (e.g., close enough) to the templates associated with the authorized user's face (e.g., static templates **216** in template space **220**). As further example, unlock threshold **264** may be represented by circle **265** in feature space **212**, depicted in FIG. **5**. As shown in FIG. **5**, feature vector **256**A is inside circle **265** and thus feature vector **256**A would have matching score **260** above unlock threshold **264**. Feature vector **256**B, however, is outside circle **265** and thus feature vector **256**B would have matching score **260** below unlock threshold **264**. In certain embodiments, unlock threshold **264** is set during manufacturing and/or by the firmware of device **100**. In some embodiments, unlock threshold **264** is updated (e.g., adjusted) by device **100** during operation of the device.

[0059] In **262**, if matching score **260** is below unlock threshold **264** (e.g., not equal to or above the unlock threshold), then device **100** is not unlocked in **266**. It should be noted that device **100** may be either locked or unlocked if matching score **260** is equal to unlock threshold **264** depending on a desired setting for the unlock threshold (e.g., tighter or looser restrictions). Additionally, either option for an equal matching score comparison may be also applied as desired for other embodiments described herein.

[0060] In some embodiments, in **268**, a number of unlock attempts is counted (e.g., the number of attempts to unlock device **100** with a different unlock attempt image captured in **252**). If the number of unlock attempts in **268** is below a selected value (e.g., a threshold), then process **250** may be run again with another unlock attempt image (e.g., a new image of the user is captured (e.g., a flood IR image or a depth map image)). In some implementations, device **100** automatically captures the new image of the user's face without prompting the user. In some embodiments, the user attempting to unlock device **100** may have additional image (s) of his/her face captured by camera **102**.

[0061] If the number of unlock attempts is above the selected value, then device **100** is locked from further attempts to use facial authentication in **270**. In some embodiments, when the device is locked in **270**, an error message may be displayed (e.g., on display **108**) indicating that facial recognition authentication process **250** has failed and/or the desired operation of device **100** is restricted or prevented from being performed. Device **100** may be locked from further attempts to use facial authentication in **270** for a specified period of time and/or until another authentication protocol is used to unlock the device. For example, passcode unlock **272** may be used to unlock device **100**. Passcode unlock **272** may include using a passcode, a password, pattern entry, a different form of biometric authentication, or another authentication protocol to unlock device **100**. In some embodiments, passcode unlock **272** includes providing a "use passcode/password/pattern" affordance that, when selected causes display of a passcode/password/pattern entry user interface, or a passcode/password/pattern entry user interface, or a "use fingerprint" prompt that, when displayed, prompts the user to place a finger on a fingerprint sensor for the device.

[0062] As shown in FIG. **7**, in **262**, if matching score **260** is above unlock threshold **264** (i.e., the user's face in the unlock attempt image substantially matches the face of the authorized user), then the matching score is compared to second threshold **274** in **276**. Second threshold **268** may be a higher threshold than unlock threshold **264** (e.g., the second threshold requires closer matching between the user's face in the unlock attempt image and the face of the authorized user and the distance between feature vectors in the captured images and feature vectors in the templates to be closer). As shown in FIG. **7**, if matching score **260** is above second threshold **274** in **276**, the user in the unlock attempt image is authenticated as the authorized user of device **100** and the device is unlocked in **278**. In some embodiments, the device is authorized to be unlocked in **278** but not unlocked unless another unlock authorization is provided (e.g., an unlock authorization from an additional authentication process such as authentication process **300**, described herein).

[0063] In certain embodiments, second threshold **274** is a threshold that is close to unlock threshold **264** to define a range of matching scores that have some uncertainty (e.g., second threshold **274** may define a small range of matching scores above the unlock threshold). In **276**, matching scores that are above second threshold **274** have already passed unlock threshold **264** but these matching scores do not provide a high level of confidence in matching between the user attempting to unlock device **100** and an authorized user defined in template space **220**. In some embodiments, the user attempting to unlock device **100** may be an additional user that has facial features that are very similar or closely related to the facial features of the authorized user defined in template space **220**. The additional user may be, for example, a sibling or twin of the authorized user that has facial features very similar to the facial features of the authorized user. The additional user may, however, not be authorized to use device **100** (e.g., be an unauthorized user). In such embodiments, the additional user may generate a matching score that passes unlock threshold **264** but is close to the unlock threshold. If only unlock threshold **264** is used for the unlocking criteria, the additional user may be able to unlock device **100** through authentication process **250** (e.g., the unlock process) even though the additional user has not been enrolled on the device (e.g., enrolled using process **200**).

[0064] Thus, in some embodiments, second threshold **274** and comparison **276** are used to trigger or activate additional authentication process **300** (e.g., a vein matching authentication process) when the user attempting to unlock the device has a matching score that is within a certain range of unlock threshold **264** (with the range being defined by the second threshold). In certain embodiments, as shown in FIG. **7**, if matching score **260** is below second threshold **274** in **276** (as well as being above unlock threshold **264**), then additional authentication process **300** is activated.

[0065] FIG. **8** depicts a flowchart of an embodiment of additional authentication process **300**. Additional authentication process **300** may be, for example, a vein matching authentication process used to distinguish between an unau-

thorized user and an authorized user that have closely related (e.g., very similar) facial features to prevent the unauthorized user from accessing device **100** without authorization. Users with closely related (or very similar) facial features include users that have facial features that are close enough in distance (e.g., as defined by feature vectors in the feature space) that the similar facial features may be clustered together and/or there is at least some overlap between the similar facial features when assessing a matching score based on the facial features. In certain embodiments, process **300** is operated by a different neural network modules and/or machine learning models than process **250**. In some embodiments, process **300** and process **250** are operated by the same neural network module and/or machine learning model.

[0066] In certain embodiments, process **300** begins with capturing one or more subepidermal images of a user's face in **302**. A subepidermal image may be captured using image sensor **103** and/or another image sensor on device **100**. In certain embodiments, the subepidermal image is captured when illuminating the face of the user with near-IR or another long wavelength illumination. For example, in certain embodiments, unlock attempt images (captured in **252** of process **250**) are captured at a wavelength in the near-IR wavelength range, as described above. The subepidermal image may, however, be captured at another wavelength that provides more light penetration beneath the skin of the user (e.g., more penetration into the subepidermal layers). For example, the subepidermal image may be captured using illumination shifted about **10** nm or more from the illumination used to capture the unlock attempt images. Shifting of the wavelength to lower wavelengths may, however, produce some light that is visible to a human eye (e.g., some light in or near the visible spectrum).

[0067] In some embodiments, the illumination for capturing subepidermal images is provided by one or more portions of illuminator **105**A and/or illuminator **105**B, shown in FIG. **2**. For example, illuminator **105**A and/or illuminator **105**B may include an array of light sources such as, but not limited to, VCSELs (vertical-cavity surface-emitting lasers). A first set of light sources in the array may provide illumination at a wavelength for unlock attempt images while a second set of light sources may provide illumination at a wavelength for subepidermal images. The different sets of light sources may be turned on/off separately to allow a specific illumination (e.g., a specific wavelength of illumination) to be provided.

[0068] In some embodiments, the subepidermal image captured in **302** is captured in association with the unlock attempt images captured in **252** (e.g., when matchings score **260** is below second threshold **274** in **276**, as shown in FIG. **7**). For example, the unlock attempt images captured in **252** may include a series of images captured over a small time frame (e.g., 60 frames in a second) to provide a set of images at a moment in time. The subepidermal image captured in **302** may be captured as a single image or a small number of images within the series of images captured for the unlock attempt images. Capturing only a single subepidermal image or a small number of subepidermal images may allow capturing of the subepidermal images to be undetected by the user even if the illumination used for the subepidermal images is somewhat visible to the human eye as described above.

[0069] In certain embodiments, the captured subepidermal image includes an image of one or more blood vessels (e.g., veins) in the user's face. FIG. **9** depicts a representation of an embodiment of an image of subepidermal features in a user's face. As shown in FIG. **9**, face **400** includes a plurality of blood vessels **402** (e.g., veins). Unlike some other facial features on the surface of the skin of a user's face, veins in the subepidermal layers of the face are typically unique to an individual and vein patterns are different between different individuals, even siblings or twins. Thus, assessment of the veins (and vein patterns) in the subepidermal layers of the face may be used to distinguish between siblings, twins, or other users with similar facial features on the surface of the face. In some embodiments, absorption properties of blood at a selected wavelength may be used to detect vein or other blood vessels in the subepidermal layers. Absorption properties of blood vessels may be useful in differentiating vein features in the eyes of the user.

[0070] In some embodiments, the captured subepidermal image includes an image of one or more localized regions of the user's face instead of the entire user's face. For example, as shown in FIG. **9**, the captured subepidermal image may only include localized region **404**. Capturing an image of a localized region of the user's face may reduce the size of the captured image and/or allow process **300** to focus on a certain region (or regions) of the face that may best be used to distinguish between different users. For example, in some embodiments, the captured subepidermal image may include an image of one or more of the user's cheek, eyes, and/or forehead. As shown in FIG. **9**, localized region **404** includes the user's cheek. These localized regions of the user's face may be used for the captured subepidermal images as blood vessels in these regions may most readily be used to distinguish between different users.

[0071] For example, FIG. **10** depicts a representation of an embodiment of an image of subepidermal features in a different user's face (e.g., a different user from the user in FIG. **9**). Face **400'**, shown in FIG. **10**, includes localized region **404'**. As shown in FIGS. **9** and **10**, localized region **404** includes a different blood vessel (vein) pattern than localized region **404'**. The differences in the blood vessel patterns of localized region **404** and localized region **404'** may be used to distinguish face **400** from face **400'**.

[0072] In some embodiments, capturing a subepidermal image of a localized region of a user's face includes directing illumination at the localized region on the user's face. For example, the light sources in the array of light sources may be individually addressable (e.g., the light sources can be turned on/off individually). In such embodiments, another process or algorithm may be used to detect where the facial regions of interest are located (e.g., where the eyes, cheeks, and/or forehead are located) on the user's face. For example, landmark feature maps may be used to identify facial features of the user in the unlock attempt images and then illumination for the subepidermal image may be directed to the localized region(s) of interest. Identification of landmark features may be accomplished as described in the copending U.S. Provisional Patent Application No. 62/556,795 to Fasel, Tajbakhsh, Wu, and Gernoth entitled "OCCLUSION DETECTION FOR FACIAL RECOGNITION PROCESSES" filed Sep. 11, 2017, which is incorporated by reference as if fully set forth herein.

[0073] After the subepidermal image is captured in **302**, process **300** may continue with encoding the captured sub-

epidermal image in **304**. Encoding of the subepidermal image may generate one or more subepidermal feature vectors **306**. In certain embodiments, subepidermal feature vectors **306** include feature vectors for veins in the captured subepidermal image (e.g., "vein feature vectors"). Subepidermal feature vectors **306** may, however, also include feature vectors for other blood vessels and/or other subepidermal features from the captured image.

[0074] In **308**, subepidermal feature vectors **306** are compared to subepidermal templates **310** to get subepidermal matching score **312**. Subepidermal templates **310** may include, for example, templates (e.g., enrollment or reference templates) for veins or other subepidermal features from enrollment images (e.g., subepidermal enrollment images captured during process **200**). Subepidermal enrollment images may be captured by capturing a single subepidermal image (or a small number of subepidermal image) in association with capturing multiple enrollment images in **204** during process **200**, as described above.

[0075] Subepidermal templates **310** may be stored separately from static templates **216** and template space **220**. In certain embodiments, subepidermal templates **310** include templates (e.g., feature vectors) from images of only selected (localized) regions of the authorized user's face (e.g., the cheek, eyes, and/or forehead). Thus, in **308** only subepidermal feature vectors **306** from these regions may be compared to subepidermal templates **310**. Comparing only in the localized regions reduces the area for comparison of subepidermal feature vectors **306** and subepidermal templates **310**. Reducing the area for comparison may improve processing speed for the comparison and utilize fewer system resources.

[0076] After subepidermal matching score **312** is obtained, the subepidermal matching score may be compared to subepidermal unlock threshold **316** for device **100** in **314**. Subepidermal unlock threshold **316** may represent a maximum allowable distance (as defined by subepidermal feature vectors) between subepidermal features of the face of the authorized user and subepidermal features of the face of the user in the captured subepidermal image that device **100** allows for unlocking of the device. For example, subepidermal unlock threshold **316** may be a value for the distance between the subepidermal features that decides whether the subepidermal features of the user in the subepidermal image is a close enough match to subepidermal features of the authorized user to allow unlocking of device **100**. In certain embodiments, subepidermal unlock threshold **316** is set during manufacturing and/or by the firmware of device **100**. In some embodiments, subepidermal unlock threshold **316** is updated (e.g., adjusted) by device **100** during operation of the device.

[0077] In **314**, if subepidermal matching score **312** is above subepidermal unlock threshold **316**, the user in the unlock attempt image and in the captured subepidermal image is authenticated as the authorized user of device **100** and the device is unlocked in **266** (also shown in FIG. **7**). In **314**, if subepidermal matching score **312** is below subepidermal unlock threshold **316**, then device **100** is not unlocked in **268** (also shown in FIG. **7**). It should be noted that device **100** may be either locked or unlocked if subepidermal matching score **312** is equal to subepidermal unlock threshold **316** depending on a desired setting for the subepidermal unlock threshold (e.g., tighter or looser restrictions).

[0078] In some embodiments, additional authentication process **300** is initiated or activated on device **100** by the authorized user. For example, process **300** may be activated in response to the authorized user providing information about one or more siblings or other people that may have closely related features to the authorized user (e.g., the authorized user may answer one or more questions regarding siblings during an enrollment or other device activation process). In some embodiments, process **300** may be activated in response to another function on the device that alerts the device that the user that has been authenticated is not the authorized user. For example, the additional user may have been authorized using process **250** but performed another function on the device that signals the additional user is not the authorized user.

[0079] In some embodiments, process **300** may be used to determine if a face in captured images is actually the face of the authorized user (e.g., the user's real face) instead of a replica of the authorized user's face. For example, an unauthorized user may attempt to unlock device **100** by wearing a mask that replicates the authorized user's face or using another replication or spoofing method. The unauthorized user may use a mask that has realistic face/skin material in an attempt to unlock device **100**. The face/skin material may, in some cases, allow the unauthorized user to unlock device **100** using process **250** without process **300** being activated.

[0080] Activation of process **300** in process **250** may, however, prevent the unauthorized user from unlocking device **100** using the mask or another spoofing method. In some embodiments, if a mask is worn by the unauthorized user (or any other user) during the image capture process for subepidermal images in process **300**, the thickness of the mask may prevent detection of any subepidermal features (e.g., encoding of the subepidermal images may not generate any subepidermal feature vectors). Thus, in such embodiments, process **300** would reject the attempt to unlock device **100** using the mask.

[0081] In some embodiments, a subepidermal image may be captured independently of process **300**. The independently captured image may be used to determine if a face in captured images is actually the face of the authorized user (e.g., the user's real face) instead of a replica of the authorized user's face (e.g., a mask). In such embodiments, capturing the subepidermal image independently allows for independent detection of the presence/non-presence of a mask without the need for activation of process **300**.

[0082] In some embodiments, the mask may still allow subepidermal features (e.g., veins) to be detected in the subepidermal images (e.g., if the mask is relatively thin or somewhat transparent). In such embodiments, process **300** may distinguish between subepidermal features of the authorized user's real face and subepidermal features of the unauthorized user using the comparison of subepidermal feature vectors in step **308**, as described above. Thus, process **300** may provide an authentication process that prevents an unauthorized user from unlocking device **100** by wearing a mask or using another face replication method.

[0083] In some embodiments, information about subepidermal features (e.g., veins or other blood vessels) may be assessed using the intensity of illumination detected on the user's face. For example, dot intensity measurements from speckle pattern illumination (and/or other structured pattern illumination) may be used to detect subepidermal features

and/or assess information about subepidermal features. Intensity lines in the speckle pattern illumination may correspond to subepidermal features such as veins. A network (e.g., a neural network) that has been trained using known mapped vein patterns may use the intensity lines to determine the presence and location of veins. In some embodiments, the network may be capable of determining the presence and location of veins using illumination at the same wavelength used for typical unlock attempt images (e.g., using near-IR wavelength illumination).

[0084] In certain embodiments, one or more process steps described herein may be performed by one or more processors (e.g., a computer processor) executing instructions stored on a non-transitory computer-readable medium. For example, process **200**, process **250**, and process **300**, shown in FIGS. **4**, **7**, and **8**, may have one or more steps performed by one or more processors executing instructions stored as program instructions in a computer readable storage medium (e.g., a non-transitory computer readable storage medium).

[0085] FIG. **11** depicts a block diagram of one embodiment of exemplary computer system **510**. Exemplary computer system **510** may be used to implement one or more embodiments described herein. In some embodiments, computer system **510** is operable by a user to implement one or more embodiments described herein such as process **200**, process **250**, and process **300**, shown in FIGS. **4**, **7**, and **8**. In the embodiment of FIG. **11**, computer system **510** includes processor **512**, memory **514**, and various peripheral devices **516**. Processor **512** is coupled to memory **514** and peripheral devices **516**. Processor **512** is configured to execute instructions, including the instructions for process **200**, process **250**, and/or process **300**, which may be in software. In various embodiments, processor **512** may implement any desired instruction set (e.g. Intel Architecture-32 (IA-32, also known as x86), IA-32 with 64 bit extensions, x86-64, PowerPC, Sparc, MIPS, ARM, IA-64, etc.). In some embodiments, computer system **510** may include more than one processor. Moreover, processor **512** may include one or more processors or one or more processor cores.

[0086] Processor **512** may be coupled to memory **514** and peripheral devices **516** in any desired fashion. For example, in some embodiments, processor **512** may be coupled to memory **514** and/or peripheral devices **516** via various interconnect. Alternatively or in addition, one or more bridge chips may be used to coupled processor **512**, memory **514**, and peripheral devices **516**.

[0087] Memory **514** may comprise any type of memory system. For example, memory **514** may comprise DRAM, and more particularly double data rate (DDR) SDRAM, RDRAM, etc. A memory controller may be included to interface to memory **514**, and/or processor **512** may include a memory controller. Memory **514** may store the instructions to be executed by processor **512** during use, data to be operated upon by the processor during use, etc.

[0088] Peripheral devices **516** may represent any sort of hardware devices that may be included in computer system **510** or coupled thereto (e.g., storage devices, optionally including computer accessible storage medium **600**, shown in FIG. **12**, other input/output (I/O) devices such as video hardware, audio hardware, user interface devices, networking hardware, etc.).

[0089] Turning now to FIG. **12**, a block diagram of one embodiment of computer accessible storage medium **600** including one or more data structures representative of device **100** (depicted in FIG. **1**) included in an integrated circuit design and one or more code sequences representative of process **200**, process **250**, and/or process **300** (shown in FIGS. **4**, **7**, and **8**). Each code sequence may include one or more instructions, which when executed by a processor in a computer, implement the operations described for the corresponding code sequence. Generally speaking, a computer accessible storage medium may include any storage media accessible by a computer during use to provide instructions and/or data to the computer. For example, a computer accessible storage medium may include non-transitory storage media such as magnetic or optical media, e.g., disk (fixed or removable), tape, CD-ROM, DVD-ROM, CD-R, CD-RW, DVD-R, DVD-RW, or Blu-Ray. Storage media may further include volatile or non-volatile memory media such as RAM (e.g. synchronous dynamic RAM (SDRAM), Rambus DRAM (RDRAM), static RAM (SRAM), etc.), ROM, or Flash memory. The storage media may be physically included within the computer to which the storage media provides instructions/data. Alternatively, the storage media may be connected to the computer. For example, the storage media may be connected to the computer over a network or wireless link, such as network attached storage. The storage media may be connected through a peripheral interface such as the Universal Serial Bus (USB). Generally, computer accessible storage medium **600** may store data in a non-transitory manner, where non-transitory in this context may refer to not transmitting the instructions/data on a signal. For example, non-transitory storage may be volatile (and may lose the stored instructions/data in response to a power down) or non-volatile.

[0090] Further modifications and alternative embodiments of various aspects of the embodiments described in this disclosure will be apparent to those skilled in the art in view of this description. Accordingly, this description is to be construed as illustrative only and is for the purpose of teaching those skilled in the art the general manner of carrying out the embodiments. It is to be understood that the forms of the embodiments shown and described herein are to be taken as the presently preferred embodiments. Elements and materials may be substituted for those illustrated and described herein, parts and processes may be reversed, and certain features of the embodiments may be utilized independently, all as would be apparent to one skilled in the art after having the benefit of this description. Changes may be made in the elements described herein without departing from the spirit and scope of the following claims.

1. A method, comprising:

obtaining one or more first images of a face of a user using a camera located on a device, the device comprising a computer processor and a memory;

encoding the first image to generate at least one first feature vector, wherein the first feature vector represents one or more facial features of the user in the encoded first image;

generating a first matching score by comparing the at least one first feature vector to a plurality of reference templates stored in the memory of the device;

comparing the first matching score to a first unlock threshold for the device;

in response to the first matching score being above the first unlock threshold, comparing the first matching

score to a second unlock threshold tor the device, the second unlock threshold being above the first unlock threshold;

in response to the first matching score being below the second unlock threshold, obtaining one or more second images of the face of the user using the camera:

encoding at least one of the second images to generate at least one second feature vector, wherein the second feature vector represents at least one vein feature of the user in the encoded second image;

generating a second matching score by comparing the at least one second feature vector to at least one vein reference template for the at least one region of the face of the user, the at least one vein reference template being stored in the memory of the device;

comparing the second matching score to a third unlock threshold for the device; and

authenticating the user to use the device in response to the second matching scores being above the third unlock threshold.

2. The method of claim **1**, wherein encoding the at least one vein feature, generating the second matching score, and authenticating the user if the second matching score is above the third unlock threshold are performed by the device in response to receiving input from an authorized user of the device.

3. The method of claim **1**, wherein the at least one image used to generate the second matching score comprises an image captured at a different wavelength from the at least one image used to generate the first matching score.

4. The method of claim **1**, wherein the at least one image used to generate the second matching score comprises an image captured with an infrared sensor that detects sub epidermal blood vessels.

5. (canceled)

6. The method of claim **1**, wherein the third unlock threshold is a threshold for matching of the at least one vein feature to at least one vein reference template.

7. The method of claim **1**, wherein the at least one region with the at least one vein feature comprises a forehead, an eye, and/or a cheek of the user.

8. The method of claim **1**, wherein the reference templates comprise feature vectors generated for an authorized user of the device.

9. The method of claim **1**, wherein the at least one vein reference template comprises feature vectors generated for an authorized user of the device and/or a pattern of veins unique to an authorized user.

10. A device, comprising:

a computer processor;

a memory;

a camera;

at least one illuminator providing infrared illumination;

circuitry coupled to the camera and the illuminator, wherein the circuitry is configured to:

obtain one or more first images of a face of a user using the camera;

encode the first image to generate at least one first feature vector, wherein the first feature vector represents one or more facial features of the user in the encoded first image;

generate a first matching score by comparing the at least one first feature vector to a plurality of reference templates stored in the memory of the device;

compare the first matching score to a first unlock threshold for the device and a second unlock threshold for the device, the first unlock threshold being below the second unlock threshold;

wherein:

if the first matching score is above the second unlock threshold, the user is authenticated to use the device; or

if the first matching score is below the second unlock threshold and above the first unlock threshold, the circuitry is further configured to:

encode at least one of the first images to generate at least one second feature vector, wherein the second feature vector represents at least one vein feature of the user in the encoded first image;

generate a second matching score by comparing the at least one second feature vector to at least one vein reference template for the at least one region of the face of the user, the at least one vein reference template being stored in the memory of the device;

compare the second matching score to a third unlock threshold; and

authenticate the user to use the device if the second matching score is above the third unlock threshold.

11. The device of claim **10**, wherein the camera comprises an infrared sensor.

12. The device of claim **10**, wherein the camera comprises an infrared sensor configured to detect sub epidermal blood vessels.

13. The device of claim **10**, wherein the at least one illuminator comprises a flood infrared illuminator and a speckle pattern infrared illuminator.

14. The device of claim **10**, wherein at least one illuminator provides at least some illumination that penetrates into a sub epidermal layer of the face of the user.

15. A method, comprising:

determining whether a vein matching operation is to be operated on one or more images of a face of a user captured using a camera located on a device, the device comprising a computer processor and a memory;

wherein determining whether the vein matching operation is to be operated comprises:

generating a matching score by comparing a first feature vector for at least one feature in the face of the user in at least one captured image to at least one feature vector from a plurality of reference templates stored in the memory of the device tor an authorized user of the device; and

determining the vein matching operation is to be operated in response to determining that the matching score is between a first unlock threshold and a second unlock threshold;

wherein the vein matching operation comprises:

comparing a feature vector for at least one vein in the face of the user in at least one additional captured image to at least one feature vector from a plurality of reference templates of vein features stored in the memory of the device for an authorized user of the device;

determining whether the face of the user in the additional captured image is the authorized user for the

device based on the comparison of the feature vector for the at least one vein and the at least one feature vector from the plurality of reference templates; and

authenticating the user to use the device in response to determining the face of the user in the additional captured image is the authorized user for the device.

16. The method of claim **15**, further comprising generating the feature vector for the at least one vein in the face of the user by encoding the additional captured image to generate the feature vector for the at least one vein.

17. The method of claim **15**, wherein determining whether the face of the user in the additional captured image is the authorized user for the device comprises:

generating a second matching score by comparing the feature vector for the at least one vein in the face of the user in at least the additional captured image to the at least one feature vector from the plurality of reference templates; and

comparing the second matching score to a third unlock threshold.

18. The method of claim **17**, further comprising authenticating the user to use the device when the second matching score is above the third unlock threshold.

19. (canceled)

20. The method of claim **15**, further comprising authenticating the user to use the device when the matching score is above the second unlock threshold, the second unlock threshold being higher than the first unlock threshold.

21. The method of claim **15**, further comprising generating the first feature vector by encoding the at least one captured image.

22. The method of claim **15**, further comprising generating the feature vector for the vein in the face of the user by encoding the at least one additional captured image.

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